Modelling of interaction between a snow mantle and a flexible structure using a discrete element method

François Nicot, Michel Gay

Natural Hazards and Earth System Sciences (2002) 2: 163–167

Natural Hazards and Earth System Sciences

Modelling of interaction between a snow mantle and a flexible structure using a discrete element method

F. Nicot[1] **and M. Gay**[2]

[1, 2]Cemagref de Grenoble, Unité de Recherche Erosion Torrentielle Neige et avalanches, France
[2]Rue de la Papeterie, BP 76, F-38402 Saint Martin d'Hères Cedex, France

Received: 20 September 2001 – Revised: 14 January 2002 – Accepted: 7 February 2002

Abstract. The search of improvement of protective techniques against natural phenomena such as snow avalanches continues to use classic methods for calculating flexible structures. This paper deals with a new method to design avalanche protection nets. This method is based on a coupled analysis of both net structure and snow mantle by using a Discrete Element Method. This has led to the development of computational software so that avalanche nets can be easily designed. This tool gives the evolution of the forces acting in several parts of the work as a function of the snow situation.

1 Introduction

1.1 Mountainous areas and snow instabilities

Mountainous areas are generally characterized by strong snow precipitation. Furthermore, these regions have common geomorphological features: erosion has formed a set of valleys whose slopes are often steep. With the effects of gravity, a snow mantle on a slope is likely to develop a mechanical instability. Its development depends on several factors such as rheological properties of the material, the kind of soil, the topography, or the climatic conditions. Snow instability induces many natural phenomena characteristic of the mountain environment during winter: avalanches, snow mantle creeping, etc.

1.2 A case of active risk intervention: snow avalanche net structures

In the case of snow instabilities, risks can be reduced in different ways. Active risk intervention aims to prevent the failure of the snow mantle and the resulting avalanche; this is possible by stabilizing the snow mantle. Passive intervention does not prevent the triggering of the avalanche, but aims to control the avalanche flow in terms of avalanche direction, velocity, width, and height. Snow avalanche net structures belong to the category of active intervention. This paper deals with the modelling of interaction between a snow mantle and such a structure. Because of their linear shape, snow avalanche net structures are often well adapted to the local topographic conditions. These structures are composed of a set of panels of metallic net, held by poles and anchors (Fig. 1). The downward movement of the snow mantle is composed of a sliding motion (translation displacement of the entire mantle considered, parallel to the ground surface), and of a repetitive motion (creeping deformation with settlement). This complex movement directs a strain field and then a stress field into the net sheets. Consequently, a reaction force is applied to the snow mantle; this force results in a stabilization effect.

1.3 Goals and methodology

From a fundamental point of view, the mechanical interaction between the snow mantle and the structure requires a coupled mechanical analysis. Avalanche net structures are an example of flexible structures. In the equilibrium state, the distribution of forces depends heavily on the strained geometrical shape of the net sheets (Nicot, 1999; Nicot, 2001). This feature is the main difference between flexible and rigid structures (Larsen, 2000). The major advantage of our approach is that the final geometrical shape of the net sheets is not assumed; generally, other methods consider a geometrical shape that is not computed, but assessed from in situ observations (Kern, 1978; Margreth, 1995). It is of a great interest to predict this final configuration as accurately as possible, because it strongly influences the distribution of forces into the structure. In this context, the new approach introduces the currently used tools and concepts from both solid mechanics (Lemaître, 1988; Sidoroff, 1984) and numerical modelling (Cundall, 1992) in order to compute the final geometrical shape. This approach is relevant to the field of avalanche control for the following reasons:

Correspondence to: F. Nicot
(francois.nicot@grenoble.cemagref.fr)

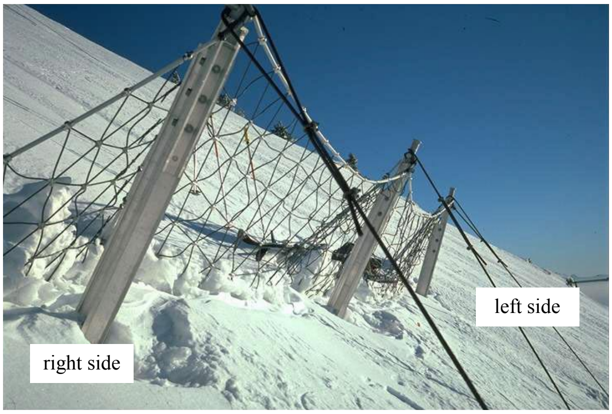

Fig. 1. Example of a snow avalanche net structure (EI Montagne).

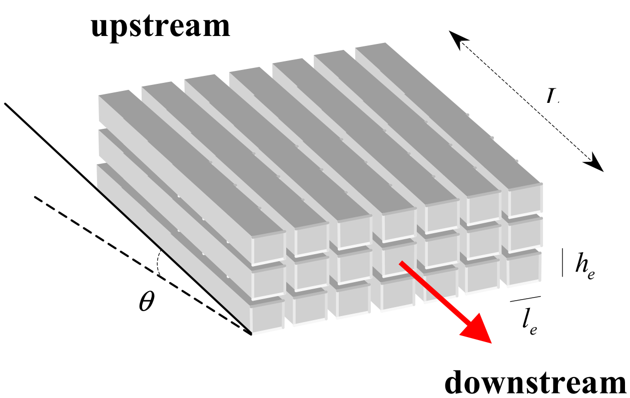

Fig. 2. Spatial description of the snow mantle.

– Initially proposing the final geometrical shape of the structure (net sheets and wires) remains problematic.

– Results from classic methods show that there is a strong relationship between the final geometrical shape and the distribution of internal forces.

2 Mechanical modelling

2.1 Spatial description

Let consider now the case of a stratified snowpack, located above a net structure, and laying on uniform slope (θ). We denote L the length of the snowpack, l its width, and H its height. It is assumed that H is uniform. The snowpack is composed of n_l layers, whose height (h_l) and length (L) are uniform. The height of the entire mantle is given by relation:

$$H = \sum_{l=1}^{n_l} H_l. \tag{1}$$

It is assumed that both density ρ_l and mechanical parameters related to the mantle are uniform within each layer "l". It can be shown (Nicot, 2002) that each layer can be described

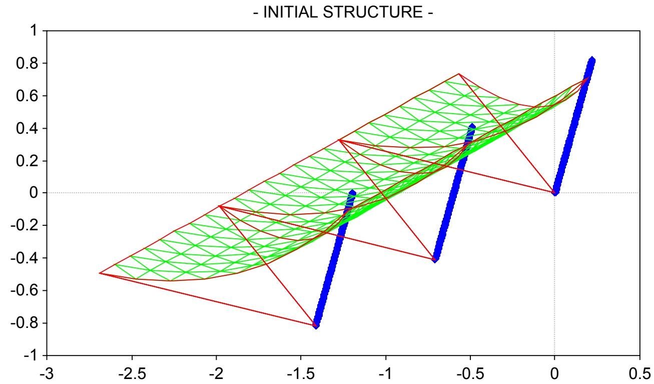

Fig. 3. Spatial description of avalanche net structure.

by a regular set of rigid parallelepipedic elements (snow elements). By denoting h_e, l_e, and L respectively the height, the width and the length of each snow element "e", the volume V_e is given by the relation:

$$V_e = h_e \; l_e \; L. \tag{2}$$

It must be noted that the sizes of h_e and l_e are very small with regard to H and l. These elements are in contact each other, and may slide downsteam (Fig. 2). The constitutive behaviour of the snowpack is modelled by a viscoplastic law (Gagliardini, 1997) which allows the contact between each snow element to be described.

The snow avalanche structure is set up along a contour line. This structure is composed of several panels of net sheet, connected to both the upstream anchors and the poles. The net sheet is composed of a regular mesh of intersected metallic wires that are fixed at each connection point. It will be assumed that each single wire belonging to the strained sheet keeps a linear geometrical shape between two intersection points. Thus, the net sheet can be described by a set of nodes located at the intersection points between single wires (Fig. 3). The straight lines which appear in Fig. 3 between each pair of adjoining nodes are for visualization purposes only. The structure is completely described by a set of nodes. That means that the contact between the snowpack and the net sheet will occur only at the nodes of the mesh, and not along the lines joining the nodes. The nodes located at the connection points between the net sheet and the poles or the anchors will be assumed to be fixed. Even if the structure gives rise to large deformation, it must be noted that strains within every single wire remain very limited. Thus, the behaviour of wires belongs to the elastic domain. In this approach, the mass of the net sheet is equally concentrated into each node, whose mass is denoted m. Initially, as suggested in Fig. 3, the net sheet is assumed to have a paraboloidal shape.

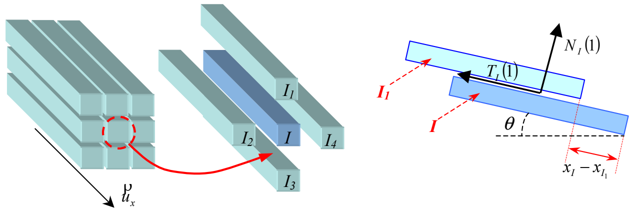

Fig. 4. Description of snow elements.

2.2 Mechanical description

2.2.1 Lagrangian description of the snowpack

Each snow element I which belongs to the layer l, is in contact with four other neighbouring elements (Fig. 4). It is submitted to the action of both its weight and a set of four contact forces $T_I(i)$. If the element is in contact with a node belonging to the net sheet, it is submitted in addition to the reaction force R_I.

The kinematics of each snow element is completely described by a single parameter x_I, which represents the total displacement of element I in direction $\boldsymbol{u}_x$. The displacement x_I of snow element I belonging to the layer l, is given by Eq. (3). If this element is not in contact with a node belonging to the net sheet, $R_I = 0$.

$$\rho_l\ V_e\ \ddot{x}_1 = \rho_l\ V_e\ \sin\theta + \sum_{i=1}^{4} T_I(i) + R_I. \tag{3}$$

The contact force $TI(i)$ is computed by integrating the shear stress $\tau_I(i)$ along the surface at the interface of the two elements I and I_i. As a first assumption, $\tau_I(i)$ is constant along this surface, and only depends on the shear strain $\gamma_I(i)$. $\gamma_I(i)$ can be assessed from the displacements of the elements belonging to the common neighbouring of I and I_i (Nicot, 2002).

2.2.2 Discrete description of the net structure

Each node J belonging to the net sheet is connected to six neighbouring nodes J_j (Fig. 5). In each fictitious single wire joining neighbouring nodes J and J_j acts an elastic force $F_J(j)$.

The vectorial location $\boldsymbol{x}_J$ of node J (mass m), in contact with snow element I, is given by Eq. (4):

$$m\ \ddot{\boldsymbol{x}}_J = m\ \boldsymbol{g} + \sum_{j=1}^{6} \boldsymbol{F}_J(j) - R_I\ \boldsymbol{u}_x\ , \tag{4}$$

with:

$$\boldsymbol{F}_J(j) = E\ S \frac{\|\ \boldsymbol{x}_{J_j} - \boldsymbol{x}_J\ \| - l_{oj}}{l_{oj}} \frac{\boldsymbol{x}_{J_j} - \boldsymbol{x}_J}{\|\ \boldsymbol{x}_{J_j} - \boldsymbol{x}_J\ \|}, \tag{5}$$

where S is the cross section of the single wire joining nodes J and J_j, l_{oj} is their initial length, and E is the elastic modulus of the steel. It is assumed that $F_J(j)$ is a tension force; thus, if $\|\ \boldsymbol{J}\boldsymbol{J}_J < l_{oj}$, $F_J(j)$ is equal to zero.

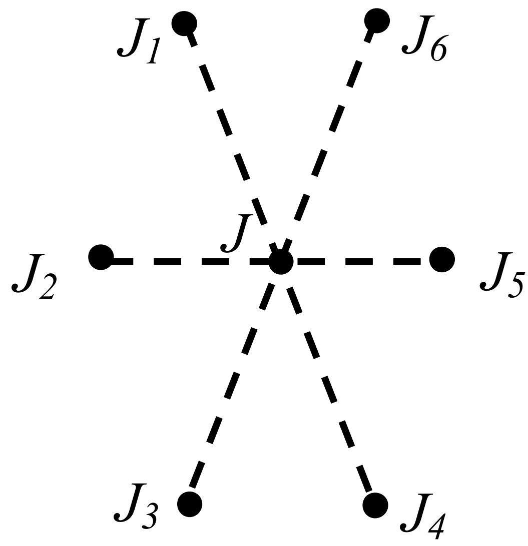

Fig. 5. Description of the net sheet. A set of neighbouring nodes.

2.2.3 Mechanical interaction between snowpack and net structure

It is assumed that during contact between a snow element I and a node J, the node does not penetrate into the element I. Thus, at each time, the incremental displacements of the two bodies I and J in direction $\boldsymbol{u}_x$ are equal:

$$\boldsymbol{dx}_j \cdot \boldsymbol{u}_x = dx_I. \tag{6}$$

This kinematic condition allows reaction force R_I to be computed.

3 Numerical modelling

Every balance Eqs. (3) and (4) can be written under the following general formulation:

$$\ddot{q}_l = f\left(q_m, \dot{q}_m\right). \tag{7}$$

An explicit numerical algorithm was developed which introduces time sampling of general Eq. (7) by using the explicit Finite Differences Method. Thus, a set of explicit equations was obtained:

$$q_I(t+\tau) = 2q_l(t) - q_l(t-\tau) + \tau^2 \\ f\left(q_m(t) \frac{q_m(t) - q_m(t-\tau)}{\tau}\right), \tag{8}$$

where τ is the time step. At each time loop, the algorithm allows the displacements of every body to be computed as a function of their previous positions. This numerical process continues until an equilibrium state between the mantle and the structure is obtained.

Table 1. Comparison between experimental and numerical results

	Internal anchor	Pre-external anchor	External anchor
Experimental result (kN)	95	111	67
Numerical result (kN)	126	115	36

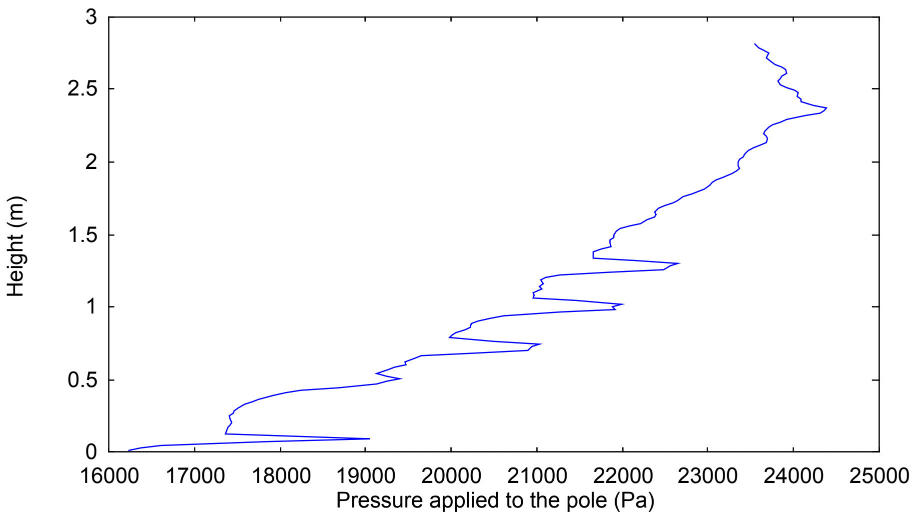

Fig. 6. Distribution of the pressure applied to the poles.

4 A tool for designing avalanche structures

The numerical algorithm has led to the development of computational software so that avalanche nets can be easily designed as a function of upstream snow conditions. It is possible to simulate several successive snow-meteorological scenarios. By changing the number of layers, their height, their density or their mechanical parameters, snowfalls or melting with settlement can be simulated. Thus, this tool allows engineers to predict the mechanical behavior of the structure during usual or unusual climatic situations. The validation of this numerical tool is in progress. During the 1999–2000 winter, several snow avalanche net structures were monitored in the French Alps. Force sensors were mounted in order to record the changes in the forces acting in the upstream anchors. Analysis of the experimental results showed that those from the site of Flaine (Haute-Savoie) provided the most reliable and useable results. Data from this site were consequently chosen for analysis. In what follows, the situation observed at the beginning of April 2000 (12 April 2000) is considered. The height of the snow mantle was equal to 3.58 m, and the average density was equal to 560 kg/m^3. These values were measured 4 m upstream of the poles. A comparison between experimental and numerical values of the forces acting in the upstream anchors is presented in Table 1. The rather good agreement between experimental and numerical values provides a first element of validation. The distribution of the pressure applied to an internal pole is shown in Fig. 6. It can be noted that the shape of this distribution is approximatively linear along the pole.

5 Conclusions and perspectives

The forces acting into a protective structure can be understood as the final result of a chain of complex phenomena: (i) snow falls, (ii) physical and mechanical evolutions of the snowpack in interaction with the climatic conditions, the ground surface, and a flexible structure, and (iii) mechanical behaviour of a flexible structure.

As a direct experimental study of the snowpack remains a very difficult task, it seems it seems reasonable to use numerical simulation to indirectly obtain information related to the snowpack. In these conditions, the net structure appears like a macroscopic but relevant sensor. This paper presents a first step in this original approach. Further studies, which are in progress, aim to validate main assumptions used above.

References

Cundall, P. A. and Roger, D. H.: Numerical modelling of discontinua, Engineering computations, 9, 101–113, 1992.

Gagliardini, O. and Meyssonnier, J.: Flow simulation of a firn-covered cold glacier, Annals of Glaciology, 24, 242–248, 1997.

Kern, F.: Calcul des efforts dans les filets paravalanches, Compte rendu de la seconde deuxième rencontre internationale sur la neige et les avalanches, ANENA, Grenoble, 241–250, 1978.

Larsen, J. O.: Design criteria for cylindrical masts exposed to snow creep forces, Snow engineering, Balkema, Rotterdam, 105–112, 2000.

Lemaitre, J., and Chaboche, J. L.: Mécanique des matériaux solides, Ed. Dunod, Paris, 163–249, 1988.

Margreth, S.: Snow pressure measurements on snow net systems, Acte de colloque, Chamonix, 241–248, 1995.

Nicot, F.: Etude du comportement mécanique des ouvrages souples de protection contre les éboulements rocheux, Thèse de troisième cycle, Ecole Centrale de Lyon, 1999.

Nicot, F., Gay, M., and Tacnet, J. M.: Interaction between a snow mantle and a flexible structure, a new method to design avalanche nets, Cold Regions Science and Technology, in press, 2001.

Nicot, F.: Modelling of a snowpack in interaction with a flexible structure by using a coupled Lagragian-Discrete approach, Mechanics of Cohesive-frictional Materials, submitted, 2002.

Sidoroff, F.: Comportement des matériaux, Ecole Centrale de Lyon, 1984.